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To investigate multiple input-multiple output saccadic eye movement neurosensory control, both three-dimensional head and two-dimensional eye movement data are recorded and analyzed. The purpose of this grant is funding computer equipment for analysis of head and saccadic eye movement data, to describe the neurosensory control mechanism response from combined visual, auditory and vestibular stimuli during enhancement and inhibitory modes. The ultimate goal of this research is to enhance our understanding of how the brain integrates and controls neurosensory information. Data analysis is carried out in both the time and frequency domain. The system identification technique is used for parameter and control estimation from the data collected. Significant advances on eye rectus muscle model development and a neural network for saccades have been made. It should be noted that the use of the equipment purchased with this grant will continue in the future. (SEE

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DURIP-Instrumentation for Recording & Analyzing Multiple Input/Output Saccadic Eye Movement Neurosensory Control

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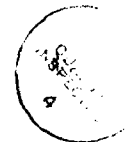North Dakota State University
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PROJECT SUMMARY

To investigate multiple input-multiple output saccadic eye movement neurosensory control, both three-dimensional head and two-dimensional eye movement data are recorded and analyzed. The purpose of this grant is funding computer equipment for analysis of head and saccadic eye movement data, to describe the neurosensory control mechanism response from combined visual, auditory and vestibular stimuli during enhancement and inhibitory modes. The ultimate goal of this research is to enhance our understanding of how the brain integrates and controls neurosensory information.

Data is recorded at Brooks Air Force Base, San Antonio Texas (in collaboration with Dr. Edward J. Engelken, NGFO) using a semi-invasive search coil system manufactured by C-N-C Engineering.

Data analysis is carried out in both the time and frequency domain. The system identification technique is used for parameter and control estimation from the data collected. Significant advances on eye rectus muscle model development and a neural network for saccades have been made.

It should be noted that the use of the equipment purchased with this grant will continue in the future. The following specific hypotheses will be tested in the near future:

1. The control mechanism for saccadic eye movements to visual and auditory stimuli is a time-optimal pulse with a smooth descent to a step waveform.

2. The multistimuli neurosensory control mechanism for head and saccadic eye movements are time-optimal.

3. The neurosensory performance of these control mechanisms can be enhanced by a proper selection and sequence of sensory inputs.

4. Neurosensory and oculomotor system function parameters can identify an operationally superior individual.

Statement of Work

The visual system is our most important sensory system. The oculomotor system is responsible for movement of the eyes so that images are centered on the central region of the retina, called the fovea. The oculomotor system responds to visual, auditory and vestibular stimuli, which results in one of five types of eye movements: saccadic eye movements, smooth pursuit eye movements, vestibular ocular movements, vergence eye movements and optokinetic eye movements. Each of these movements are controlled by a different neuronal system. All of these controllers share the same final common pathway to the extraocular muscles. In addition to the five types of eye movements, these stimuli also cause head and body movements. Thus, the visual system is a multiple input-multiple output system. Because of the importance of fast or saccadic eye movements in scanning for objects of interest in space, saccadic eye movements will be the major focus of this investigation.

Numerous investigations, particularly in recent years [1]-[7], have greatly contributed to our knowledge of the elementary control mechanism during saccadic eye movements. Yet, many aspects of the basic control mechanism during saccadic eye movements are still uncertain [8].

The central nervous system (CNS) processing of multisensory information is quite complex and not well understood. Visual, auditory and vestibular sensory data are all initially encoded in various frames of reference which are different from the coordinate system of the eyeball. This sensory data must be translated into a common coordinate system by the CNS, and then sent to the extraocular muscles along the same final common pathway. The translation of sensory data must be combined with CNS information about the current position of the eyes and the head to direct the eyes to the target location. While a common coordinate system for translation of sensory data exists, its description is unknown at this time [5]. Furthermore, the interaction among multisensory data, and how conflicting information is arbitrated, is not well understood [5]. Numerous investigators have examined the single stimulus CNS response to visual, auditory or vestibular stimuli. While attempts have been made to examine how the human CNS integrates and processes multisensory information from combined visual, auditory and vestibular stimuli to direct the head and eye responses, much remains unknown. Most researchers have investigated animal model multisensory stimuli sensorimotor integration from an electrophysiological, anatomical and a neural pathway methodology (see Sparks for a current review of the literature [5]). However, since little is known about the detailed intrinsic organization of the superior colliculus and the response properties of the cells of origin for the major efferent pathways, the anatomical and neural pathway methodology is not sufficient alone to be useful in constructing a comprehensive model of the CNS control of multisensory information [5]. A special need for additional approaches is identified by Sparks as necessary to help delineate the CNS control of multisensory information [5].

The effect of combinations of sensory stimuli on the head and saccadic eye movement response has been studied by Meredith and Stein [9]. They examined cell responses in cat and hamster to combinations of visual, somatic and auditory stimuli, and noted dramatic enhancement and inhibitory effects in microelectrode studies. The effectiveness of each stimulus is noted to be a function of the environment, that is, auditory stimuli are more effective in darkness or low level illumination, whereas visual stimuli are more effective in higher levels of illumination. Moreover, the responsiveness of one stimulus can dramatically affect the responsiveness of other stimuli.
The neural response to combinations of sensory stimuli all flow along the same common pathway to the extraocular muscles to control saccadic eye movements.

The functional consequences of combined stimulus interactions is not well understood. Certainly, a saturation phenomenon occurs in the neural control mechanism to combinations of sensory stimuli. Thus, the control signal generated by the neural control mechanism does not equal the sum of the controllers for each separate stimulus. Meredith and Stein noted that knowledge of cell responses to individual stimuli could not predict the response to combined stimuli [9]. Furthermore, the CNS processing of sensory stimuli occur in different locations of the brain, thus, (stochastic) timing differences may be important.

Investigators have reported a tightly coupled relationship between eye and head movements toward visual targets in monkeys [10],[11]. Moreover, a time optimal control mechanism for human head rotations has been postulated [12]-[17]. Coordinated eye and head movements have not yet been identified as time optimal. Qualitatively, a natural orienting movement to a visual target typically involves the following three steps [18]. First, a saccadic eye movement is executed which moves the eyes towards the target. Approximately 25 to 40 msec after the saccadic eye movement begins, a head movement of the same magnitude as the eye movement is executed. Finally, as the head moves, a vestibular response due to the head motion causes the eyes to be rotated in the opposite direction that the head is moving. Other investigators have indicated the rotation of the eyes during the head movement is not caused by a vestibular mechanism, but by a reset mechanism [19].

Despite many experimental studies which qualitatively describe eye and head coordination [10],[11],[19]-[22], a quantitative description of the eye and head neural control mechanism has not been reported, particularly small amplitude target movements under 15 degrees. Two specific qualitative head movement patterns have been identified. For small amplitude target stimuli (under 15#), the majority of responses involved movement of the eyes only, the head voluntarily remained fixed [20]. For large amplitude target stimuli (greater than 15#), almost all responses involved coordinated eye and head movement [10],[11],[19]-[22]. Neither the head movement paradigm or the neural control mechanism has been reported in these studies. However, some investigators have noted a neural control strategy which operates to maintain the fovea on the target [20],[22].

Analysis of EOG data indicates that the peak velocity of large amplitude saccades are lower during combined eye and head movement than when the head was restrained [21]. Clearly, small amplitude saccades have the same peak velocity since there is no head movement. From Fig. 1 in Morasso et al. [21], it appears that the time to complete the saccadic eye movement is shorter during the combined eye and head movement than in the case where the head was restrained. Since visual perception is suppressed during a saccade, minimizing saccade duration is important [23],[24]. Thus, it appears that for a large target amplitude, combined head and eye movements might restore visual perception faster than an eye movement.

To direct the eyes towards a target, one possible neurosensory control mechanism for head and eye movement is to minimize the saccade duration. This is a time optimal controller. Such a controller would explain why most naturally occurring saccades are less than 15 degrees in amplitude, with no head movement [25]. A small amplitude eye movement is executed without a coordinated head movement since the head movement does not decrease the time it takes to move the eyes onto the target because of inherent time delays. Moreover, a combined head and eye movement is executed when target amplitudes are larger than 15 degrees since it takes less time to move the eyes to the target than with an eye movement only.

Saccadic Eye Movements

Saccadic eye movements, among the fastest voluntary muscle movements the human is capable of producing, are characterized by a rapid shift of gaze from one point of fixation to another. Stimulated by target displacement, information from the retina periphery is used to direct the eyeball to place the high resolution fovea on the target. Neglecting vestibulo-ocular input, saccadic eye movements are conjugate and ballistic with a typical latency of 150-300 milliseconds. The latent period is thought to be the time interval during which the CNS calculates the distance the eyeball is to be moved, transforming retinal error into transient muscle activity.

A large variability in saccade dynamics exists, either executed by a single subject or a group of subjects, for saccades of the same size [29],[30]. Saccade peak velocity, time to peak velocity, duration and latency are observed to exhibit random behavior under conditions without the influence of fatigue or drugs [7],[29]-[31]. These variations have been attributed to stochastic motoneuronal activity that is first-order time-optimal [6]-[7],[29]-[31].

Oculomotor System

Models of oculomotor function are important in the development of clinically useful diagnostic tools and in understanding the neurophysiology of eye movements [2],[32]-[38]. The complexity of these models and their correlation with physiological evidence has increased since Westheimer first presented a model of saccadic eye movements in 1954 [39]. Recently, a sixth-order linear homeomorphic horizontal saccadic eye movement model was developed that provides an excellent match between the model predictions and the data [40]. Enderle et al. modified the linear homeomorphic horizontal saccadic eye movement model to a form that makes it ideal for use in the development of more sensitive tests of oculomotor pathology and in the description of normal oculomotor function [41].

Head Movement System

Recently, a sixth-order nonlinear model of horizontal head movement was developed which describes the movement of the head and neck [12]-[17]. Based on EMG recordings, these investigators have postulated a time-optimal neural control mechanism for an individual voluntarily rotating their head from one position to another. Head position was recorded in these studies using the potentiometric method and not from the more accurate magnetic field method. Additionally, these studies examined subjects rotating their heads only; natural head and eye movement rotations where not examined.

Saccadic Neuronal Control Mechanism for a Visual Stimulus

Although the purpose for a saccadic eye movement is clear, that is, to quickly redirect the eyeball to the destination, the neuronal control mechanism is not. Direct evidence through electrophysiological techniques have demonstrated that activity patterns of motoneurons during visually elicited saccades are manifested by a pulse-step discharge rate [8],[42]-[44]. Saccades are initiated by high frequency bursts of motoneuron discharge (pulse) in the agonist muscle on top of the fixation rates necessary to keep the desired eye position (step). The motoneuron discharge rate in the antagonist muscle is completely inhibited during the pulse portion of the saccade.

While this general pattern of motoneuron activity is qualitatively accepted during a saccadic eye movement, there is little agreement on a quantitative

discharge description [44]. These conflicts reported in the literature are attributed to the stochastic nature of the system and an apparent misinterpretation of microelectrode recordings [44].

A number of theories have been reported that describe the control of saccadic eye movements [1]-[4],[6],[45]. Enderle and Wolfe have presented a new theory describing the time-optimal control of saccadic eye movements based on Pontryagin's minimum principle and physiological considerations [6]. Using the modified linear homeomorphic model [7],[41], they determined that the saccadic eye movement system operates under a first-order time-optimal neuronal control mechanism [6]. The concepts underlying this hypothesis are that each muscle's active state tension is described by a low-pass filtered pulse-step waveform in which the magnitude of the agonist pulse is a maximum regardless of the amplitude of the saccade, and that only the duration of the agonist pulse affects the size of the saccade. The antagonist muscle is completely inhibited during the period of maximum agonist muscle stimulation. Two methods were used to solve for the switch-times for the time-optimal controller, the gradient method and the direct method: only the direct method gave robust results.

From this time-optimal control investigation [6], Enderle and Westine have developed a new stochastic local feedback neural circuit control model for horizontal saccades [45]. The saccade burst generator is first-order time optimal and located in the superior colliculus. Additional components of the saccade generator model consists of burst, tonic and pause premotor cells. In the solution for the optimal control for the time-varying oculomotor system, Enderle and Wolfe assumed that the input must be bang-bang as illustrated in their Figure 2 [6]. Of special interest is the activity of the neural control after the switch-time t_1. In bang-bang problems, the optimal control for minimum time is a maximum effort throughout the interval of operation [46]. This situation is not precisely met in the oculomotor system because of the need to have a steady state neural control to maintain the eyeball at the destination. During the time after t_1, the optimal (unsaturated, not bang-bang) controller should be determined from the Euler-Lagrange equations; unfortunately the standard approaches do not yield robust results. Thus, while the bang-bang control may be applicable in this circumstance, the optimal control should be further investigated using a technique (such as Rosen's method [47]-[49]) that does not require the bang-bang assumption. Further analysis of the time-optimal control of saccadic eye movements using Rosen's method should yield controller results that are not a precise pulse-step waveform. After the agonist pulse, it is expected that there is a smooth decay from the control at the switch-time t_1 to the steady state control necessary to keep the eyeball at the destination. This type of controller is illustrated in Fig. 3 from Fuchs and Luschei [43].

These postulated results should change our understanding of the control of saccadic eye movements and the explanations for clinical disorders of ocular movement. Since the postulated neural controller is modified, a new cause(s) for dynamic overshoot and undershoot, and glissades must be investigated (for example, see [45] for a new mechanism describing these normal behaviors). Furthermore, these results should be useful to investigators examining motoneuron firing patterns using electrophysiological techniques (see [44] for a more extensive explanation), and for updating forthcoming neural burst generator models.

Saccadic Neuronal Control Mechanism for an Auditory Stimulus

Studies of saccades elicited from auditory stimuli (auditory saccades) have been reported by a number of investigators, but not to the same extent as visually elicited saccades (visual saccades) [50]-[57]. These studies have primarily examined the auditory saccadic response characteristics (latency, accuracy and peak velocity), and compared the auditory and visual saccadic response characteristics. Zahn et al. and Zambarbieri et al. reported that auditory saccades were slower, slightly less accurate, and had longer latency than visual saccades [51]-[54]. However, Whittington et al. reported that auditory saccades had shorter latencies than visual saccades [56].

Engelken has reported that the latency and manual reaction time differences reported by these investigators [51]-[54] is due to problems with the experimental methods [57]. In studies conducted by Engelken in an anechoic room, auditory saccade latency and manual reaction time are found to be exponential functions of target amplitude. This relationship is attributed to the increased time needed to process the interaural time, and intensity differences required to determine target position. Apparently, the size of the generated signal in the auditory system depends on the size of the target amplitude. Thus, detection of small target displacements takes longer since the smaller displacements constitute weaker stimuli. These findings correctly predict that auditory saccade latency decreases as target eccentricity increases. Furthermore, by increasing the intensity of the auditory stimuli as a function of target amplitude, auditory saccade latency may exhibit target amplitude independence similar to visual saccade latency.

Auditory saccades have lower peak velocities and longer durations than visual saccades [50]-[57]. There have been no studies which have quantitatively detailed the auditory saccadic neural control mechanism. However, some investigators have postulated that the auditory saccadic control mechanism is similar to the visual saccadic control mechanism [54],[55]. In all likelihood, the auditory saccadic control mechanism is a first-order time-optimal neural control mechanism (similar to the visual saccadic neural control mechanism [6]). Any differences between the controllers might possibly be attributable to the population differences between bursting neurons in the superior colliculus. Motoneurons burst well beyond rates at which the oculomotor muscle can respond during visual saccadic eye movements [43]. This higher level of bursting significantly contributes to a faster eye movement [41]. It may be possible that the differences noted in saccade peak velocity are related to this excess bursting during visual saccades and absence during auditory saccades. Moreover, the effect of auditory stimulus intensity may also affect the bursting rate of auditory neurons in the superior colliculus.

Saccadic Neuronal Control Mechanism for Bisensory Stimuli

The effects of auditory and visual stimuli manual reaction time (MRT) have been investigated by a number of researchers [57]-[61]. In all, these investigators demonstrated a 12 to 18% reduction in MRT using bisensory stimuli. Engelken has also investigated saccade latency and MRT with similar findings [57]. These findings suggest that a proper combination of auditory and visual stimuli may decrease the saccadic eye movement latency, and modify velocity, duration and accuracy characteristics as well.

Engelken has also studied the saccadic response to visual stimuli with an auditory cue [57]. An auditory cue indicates when the target moved, but does not provide any localization information. He reported a significantly shorter saccade latency with an auditory cue than without an auditory cue. Reported

auditory cue saccade latencies are similar in size to bisensory saccade latencies. The auditory cue may provide a reset mechanism for detection of target motion.

Coordinate System

Currently, visual targets are thought to be represented in spatial rather than a retinocentric coordinate system [2]. With the head stationary, the retinal error is combined with eye position in the head to produce a response signal. Auditory targets are also thought to be represented in a spatial coordinate system.

Traditional models of the saccadic system supported a retinotopic theory of saccade programming [62]. In these models, a retinal error is generated when an interesting target moves to the peripheral visual field. The magnitude and direction of the eye movement required to bring the image of the target to the fovea is calculated from the retinal error and the proper neural signals are generated to execute the movement.

Specific aims of the proposed research

The objective of the proposed research is to use systems analysis to investigate and integrate the head and saccadic eye movement neurosensory control mechanism response from visual, auditory and vestibular stimuli. Additionally, smooth pursuit performance between pilots and normal subjects, saccadic eye movement performance between NDSU baseball players and normal subjects will be investigated to detect neurosensory and oculomotor system function differences. A longitudinal study to investigate important oculomotor and neurosensory control parameters correlation with operationally superior performance will also be undertaken.

Previously, we demonstrated the operation of a time-optimal control mechanism during horizontal visual saccadic eye movements [6] [7] and postulated stochastic local feedback model for horizontal saccades [45]. To more fully examine time-optimal control during visual saccadic eye movements, Rosen's technique [47]-[49] will be used to remove the limitations imposed in our previous study [6]-[7]. This technique will also be used for the time-optimal control investigation of auditory saccades, and bisensory saccades during head and eye movements. These results are significant in that the derived time-optimal control mechanism may be responsible for all neurosensory control. Additionally, we have demonstrated that it is possible to reduce the total duration of a saccadic eye movement using bisensory stimuli [57]. Specifically, saccadic performance is enhanced by adding an auditory cue to the visual stimuli or by using bisensory stimuli, which acts to reduce the latent period. At this time, it is uncertain whether there are any further changes in the neurosensory response. We intend to fully investigate further enhancement modes of saccadic performance, focusing on bisensory timing and intensity, and the effects of external conditions.

The purpose of this investigation is to examine the head and saccadic eye movement neurosensory control mechanism response elicited from combined visual, auditory and vestibular stimuli during enhancement and inhibitory modes. The specific hypotheses that will be tested include:

1. The control mechanism for saccadic eye movements to visual and auditory stimuli is a time optimal pulse with a smooth descent to a step waveform.

2.	The multistimuli neurosensory control mechanism for head and saccadic eye movements are time optimal.

3.	The neurosensory performance of these control mechanisms can be enhanced by a proper selection and sequence of sensory inputs.

4.	Neurosensory and oculomotor system function parameters can identify the operationally superior individual.

The ultimate goal of this project is to enhance our understanding of how the brain integrates and controls neurosensory information. The insight gained in this study is directly applicable to clinical applications involving sensory tests for the assessment of motoneural activity and changes caused by fatigue, aging, alcohol, drugs, or pathology. Additionally, this research is of potential interest to the armed forces due to the importance of fighter pilot visual sensory information in air-to-air operations. Understanding the visual system, and especially the neurosensory control mechanism, may provide further insight into how the brain functions. Moreover, accurately describing the neurosensory control mechanism of the visual system may be important in predicting performance in environments or occupations where optimal neurosensory and motor system function are essential to survival [63]. For example, combat pilots of the future may view a synthetic display of the cockpit and its instruments through a helmet contained stereographic optics system, an environment where neurosensory performance may be critical for the successful pilot.

Discussion of Tasks

This study of neurosensory control is partitioned into tasks, all designed to increase our understanding of how the brain integrates and controls information. Only by a systematic study of these tasks of increasing complexity is it possible to gain an understanding of all the experimental data. The first task involves a theoretical investigation. The remaining tasks involve experimental investigations.

System analysis and identification is a technique that is useful in studying phenomenon behavior and control and has been credited as a major contributing factor in the rapid advances in neurosensory control. The system identification technique, a frequency response method, has been successfully used to determine the saccadic neural control mechanism from a visual stimulus [7]. From these results one can infer motorneuronal activity, deduce the CNS control strategy, and observe changes in the control mechanism. The system identification technique can also be used to estimate the CNS control mechanism response from multisensory information. Furthermore, the application of the system identification technique to multisensory control can be used to determine the common coordinate system for translation of sensory data, and describe the interaction among multisensory data and how conflicting information is arbitrated. An analytical model of this control mechanism will be postulated and rigorously tested against experimental data, and compared with published anatomical and physiological results. The significantly improved accuracy of the proposed equipment is important for examining the initial and final portions of the trajectory. The effects of the initial conditions and external conditions, such as auditory and visual noise, and moving peripheral backgrounds will be carefully investigated in each of these tasks.

Task 1

The time-optimal control of saccadic eye movements due to a visual stimulus will be further analyzed (theoretically) using Rosen's method [47]-[49]. Rosen's method is an iterative numerical procedure for minimizing a function of several variables, ideally suited to problems with constraints. The strength of Rosen's method matches the situation present in the saccadic eye movement problem. This method does not require an assumed solution, as in the direct method, nor does it involve solving the costate equation, as in the gradient method. Thus, the difficulties associated with both the direct method and the gradient method are avoided with Rosen's method. The problem statement is given in equations 1 through 5 of Enderle and Wolfe [6]. The Rosen method solution requires that the problem statement be transformed into a discrete problem by approximating differential equations by difference equations and the integral in the performance measure by a summation. The optimal control is then iteratively solved to minimize the performance measure using the gradient projection theorem. The optimal control for zero initial conditions and nonzero initial conditions will be investigated. The results of this analysis have a direct influence on the proposed controller for both the visual and auditory input stimuli. Additionally, this same controller has an influence on any proposed controller for the two input-single output and three input-two output cases.

Task 2

Next, the system identification technique will be modified to incorporate the previous findings, and to use a possibly more accurate frequency spectrum technique called data dependent systems (DDS) analysis [66]-[67], to improve the accuracy of the parameter estimates. Naturally, if the form of the neural controller is changed according to the results of task 1, the system identification techniques to estimate oculomotor parameters and neural controllers presented by Enderle and Wolfe will need to be changed accordingly. Estimation of parameters using nonlinear regression analysis (in the time domain) will be used if significant problems develop with the system identification technique. Nonparametric spectral estimation in the system identification technique is implemented with a fast Fourier transform (FFT) algorithm [7]. Burrow and Enderle have described an accuracy advantage of DDS over the FFT (illustrated in their Figures 1-3) [67]. DDS is a systematic implementation of linear predictive coding techniques. The system is modeled as an output from a linear time-invariant system excited by a hypothetical discrete white noise input sequence with zero expectation and constant variance (an autoregressive moving average model (ARMA)). With DDS incorporated in the system identification technique, the accuracy in the oculomotor system parameters and neural controllers may be significantly improved. While it is impossible to analytically separate the agonist and antagonist neural controllers, it is possible to investigate their combined affect, the plant input, as detailed by Enderle et al. [41], using inverse modeling. Using derivative filters and the parameter results from the system identification technique, one can experimentally estimate the plant input from the eye movement data using equation 10 of Enderle et al. [41]. For saccades over 15o, only the agonist input is present. Thus, the agonist input can be estimated directly. From the estimate of the plant input, one can infer neural controller activity.

Although a numerical sensitivity analysis has been previously reported in the literature for the linear homeomorphic eye movement model [68],[69], no new sensitivity analysis has been reported on the new set of oculomotor parameters presented in the modified linear homeomorphic saccadic eye movement model [41]. It is proposed that a sensitivity analysis be carried out here for the modified linear homeomorphic saccadic eye movement model.

Task 3

An experimental single stimulus-single response investigation will be carried out separately for visual and auditory inputs to determine the neuronal controller with zero initial conditions and nonzero initial conditions. First, the parameters for the oculomotor plant will be determined along with the neural controller for visual saccadic eye movements using the system identification technique. Then, the neural controller for auditory saccadic eye movements will be evaluated using the system identification technique and inverse analysis. The inverse technique is used to first examine the shape of the plant input (as detailed in task 2). Unless evidence exists to the contrary, the shape of the neural controller for auditory saccades will be the same as visual saccades. The inverse technique is used to confirm this hypothesis. Additionally, the effects of external conditions on each of the stimulus inputs will be investigated. A low level background auditory noise, a stochastic visual dot pattern, and a moving periphery background will be used to determine any changes in the neural control mechanism. A projector which uses computer generated pictures will be purchased with this equipment grant. Of particular interest is determining whether any significant differences exist in the pulse magnitude, the switch time, and the latent period among the stimulus inputs. While all neural inputs follow a final common pathway, the neural inputs are generated in different regions of the CNS for each of the stimuli. Thus pronounced differences are expected in the stimulus saccadic eye movement response.

Task 4

A two input-single output analysis will be carried out, as illustrated in the following figure, to determine the neuronal control mechanism for the saccadic eye movement response to combined visual and auditory input stimuli with zero and nonzero initial conditions. This analysis will be carried out with the head fixed. The visual and auditory input stimuli will be under computer control.

As before, inverse analysis on experimental data will be used to examine the shape of the controller. System identification techniques will then be used to estimate the neural controller x. The multisensory controller will be carefully compared with the single stimuli controller. Additionally, the effects of external conditions on the stimulus inputs will be investigated. A low level background auditory noise, a stochastic visual dot pattern, and a moving periphery background will be used to determine any changes in the neural control mechanism. Of particular interest is the significance of the timing of the two input stimuli for enhancement of saccadic response. To examine the effect of timing differences on the saccadic eye movement response, delays will be incorporated in the initiation of the input stimuli (such as applying the visual stimuli T msec after the auditory stimuli, $0 < T < 50$, and vice versa). As indicated, a significantly smaller latent period is observed with bisensory stimuli [56], but the effects on the saccade dynamics is uncertain.

Task 5

A three input-two output analysis will be carried out, to determine the neuronal control mechanism for the head response and saccadic eye movement response to visual, auditory and vestibular input stimuli.

A theoretical investigation of the time-optimal neurosensory control mechanism for the eye and head movement system will be carried out using Rosen's method [47]-[49]. It will be interesting to examine whether there are two modes of operation as previously discussed. Furthermore, it will be interesting to determine whether the response can be enhanced. Inverse analysis on

experimental data is first used to examine the shape of the controllers.
Multisensory interactions will be carefully compared with the single stimuli case.

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LIST OF PUBLICATIONS

The following are publications generated through use of the computer equipment purchased with this grant. The Program Manager (Dr. John Tangney) has copies of all of the completed manuscripts.

Enderle, J.D., Weigel, R.B., and Engelken, E.J., Inverse Technique Applied to Saccadic Eye Movements. In preparation for submission for publication in the *IEEE Transactions on Biomedical Engineering*, April 1990.

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